*Agricultural biotechnology and oil crops – current uncertainties and future potential**

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Introduction

Plant biotechnology, also referred to as agricultural biotechnology or "agbiotech", can be defined as the use of modern methods of molecular and cell biology for the improvement of crops. This may involve the use of recombinant DNA techniques to create transgenic crops that contain novel genes. But it can also involve the use of DNA marker technology in advanced breeding programmes or the use of cell and tissue culture for crop improvement without resorting to transgenesis. In contrast to traditional biotechnology, where microorganisms are used for applications like bread making, cheese making or alcoholic fermentation, agbiotech is still a relatively new endeavour that has been going for only a few decades. For many millennia, plants have been used by human societies as sources of a vast array of important products. Plant products like starches, proteins and oils in seeds, are raw materials for most of our food and animal feedstuffs. Plants are also the major sources of fibre for building materials, clothing and paper. Many of our leading drugs were originally or still are derived from phytochemicals, e.g. aspirin or taxol. Therefore the possibilities for improving current products and making new products by means of plant biotechnology are, in principle, almost limitless. It is considered by many scientists that the tools of plant biotechnology offer humankind one of its most significant opportunities to manage the ever growing and ever changing demands for food, feed and fibre production, while also contributing to the sustainability of agriculture.

This optimistic view of agbiotech is challenged by many other groups and individuals, especially in Europe. To some extent the reservations about agbiotech are based on attempts to rapidly commercialise transgenic crop technology during the 1990s before some of the more consumer-attractive products have been developed. The first generation of so-called GM crops (Genetically Modified – in the sense of the addition of exogenous DNA) are modified for so-called "input traits", e.g. herbicide tolerance or insect resistance. These input traits may be attractive to seed companies or growers, as they can lower marginal expenses and increase revenues, but they do not normally improve crop quality, nor do they result in lower retail food prices. Therefore, GM crops modified for input traits give no direct benefits to consumers of the crop products, i.e. supermarket shoppers. However, in labs around the world, scientists are now developing a much more diverse range of "second generation" GM crops. In many of these newer transgenic crops, the manipulation of output (or quality) traits may render them more appealing to consumers in the future. Another important consideration that is often overlooked is that many techniques of plant biotechnology can also be used for crop improvement without necessarily involving gene transfer. For example, DNA markers and other genomic technologies can be used in advanced breeding programmes either with existing crops or to domesticate entirely new crops. In this review, I will discuss the current situation of agbiotech and the future prospects for the industry, particularly as applied to oil crops. In addition to considering some of the many possible uses of GM crops, particularly stress will be laid on the many non-transgenic applications of agbiotech.

From the beginnings to the present

Most applications of modern plant biotechnology can be considered to involve the manipulation of DNA sequences originally isolated from plants or other organisms. This technology was originally invented in the 1970s when it became possible to purify and amplify DNA sequences from bacteria. This was followed in the 1980s by the invention of various methods for the transfer of exogenous DNA into plants, either directly or via vector organisms, most notably *Agrobacterium tumefaciens*. The purified DNA sequences can be used in two main ways. First, they may be inserted, in the form of coding regions and other functional regions such as promoters, introns and terminators, into a plant in order to confer new physiological properties or to make new products. Second, the purified DNA sequences can be used as genetic markers to assist in the selection of chromosome segments and hence phenotypic characteristics in progeny of sexual crosses as part of plant breeding programmes.

In considering this topic it is important to bear in mind that plant biotechnology cannot be considered solely as a context-free scientific discipline. The very term "biotechnology" implies an application of scientific principles for a specific human purpose – such as the "improvement" of agriculture as defined by the criteria adopted by the major global trading blocs. Many of the assumptions underlying these criteria are not shared by groups such as vegetarians, organic farmers or others pressing for less intensive modes of agricultural production, not to mention wide swathes of the developing World where these applications are deemed to have little relevance at present. The opposition to the commercial application of plant biotechnology for the production of transgenic crops has already led to the imposition of an effective moratorium, from 1999, on the commercial cultivation such crops throughout the European Union. This is important because the EU is the second wealthiest trading bloc in the world after the USA (gross domestic product of the EU is currently estimated at $8 trillion versus $10 trillion for the USA (http://www.forbes.com/home/2002/10/21/1021topnews.html). There are many websites devoted to information exchange and discussion on the various ethical, social, economic and scientific aspects of agbiotech. Some of these sites tend to be polarised towards strong pro- or anti-biotech views, but some of the more balanced sites can be found as follows (http://pewagbiotech.org; www.isaaa.org; http://www.scidev.net/dossiers/gmcrops; http://www.biotech-info.net).

The dichotomy between the EU and US positions on transgenic crops was clearly illustrated by two events in July 2002. On the one hand, the European parliament voted for a stringent new law to restrict the sale of products derived from transgenic crops and require the labelling (as GM-derived) of any product containing more than a 0.5% presence of a derivative of a transgenic crop. If approved, this law would even apply to highly refined products of transgenic crops, such as solvent-extracted oils, where there is no residual transgenic DNA. On the other hand, in America the USDA released figures showing that the acreage of transgenic crops grown in the US during 2002 had increased by 13% from 2001 levels, which themselves were substantially up on previous years. Some three quarters of the US soybean crops was transgenic in 2002 as was over 70% of the upland cotton and one third of the corn (maize).

Despite strong opposition by many vocal groups in Europe, there are increasing signs that some transgenic crops are beginning to find more general favour in a number of developing countries, especially where there are obvious benefits to local farmers. In March 2002, the Indian government approved the commercial cultivation of three genetically modified cotton hybrids, which could give higher yields and reduced pesticide inputs, and also indicated that it was looking seriously at several other GM crops, including mustard. This action came only a few months after the government had ordered the destruction of 10,000 hectares of genetically modified cotton crops in Gujarat state after protests by environmental activists who claimed they posed health and environment risks. Even where GM crops have not been authorised in India, there have been reports of farmers growing "pirated" GM crops, like Bt cotton, where there may be worthwhile cost savings to the grower (Copple B, 2002). Meanwhile China continued to increase its GM crop acreage to become the fourth largest global producer in 2002. Also in 2002, both China and India significantly eased restrictions on the import of

GM foods. One effect of a further European Union decision on GM food labelling in October 2002 may be to open up their markets to GM imports in the future. However, whether consumers will actually buy GM labelled food products remains much less certain. Therefore, while the situation regarding the commercialisation of transgenic crops remains finely balanced in Europe, many of the world's largest agricultural producers and consumers, especially in some of the rapidly expanding Asian economies, now appear to be increasingly in favour of the technology.

Non-transgenic uses of agbiotech

The development and release of commercial transgenic crops is the most widely publicised application of plant biotechnology, but is arguably less significant than the deployment of molecular genetic methods and tools for the recognition, selection and breeding of improved non-transgenic crops. In the early years of the 21st century, the most widespread use of such agbiotech methods is in support of conventional breeding programmes, where new molecular markers and tissue culture techniques are already having a considerable impact in the improvement of dozens of different crops.

DNA marker-assisted selection

Plant breeding has always relied on the selection of agronomically favourable characters from the diverse gene pool that is present in any crop species, even if many elite commercial cultivars tend to be highly inbred. Often these agronomic characters are visible and easily identified, *e.g.* height or flower colour or resistance to fungal attack. In other cases, the characters can be much more subtle and sometimes can only be measured by sophisticated analytical techniques, *e.g.* the amounts of certain secondary products or the fatty acid composition of the seed oil. In all of these cases, it was formerly necessary for the breeder to grow up and analyse each new generation before it was possible to measure the character, or phenotype, and select the appropriate plants. The advent of marker-assisted selection has changed this as breeders can now select a few plants that are likely to express the required characters from amongst tens of thousands of progeny even before the plants have developed to maturity. The basis of the method is DNA-fingerprinting and is in principle no different from the methods used to great effect in modern medical diagnostics or in forensic science (Gill, 1985).

Molecular markers such as microsatellites, RFLPs (restriction fragment length polymorphisms) and RAPDs (random amplified polymorphic DNA) have now been developed for many crops, including trees like oil palm. These markers can be assembled into genetic maps that have considerable utility both in basic biological research and in commercial breeding programmes. The markers can be used to track the presence of valuable characters in large segregating populations as part of a crop-breeding programme. For example, if a useful trait like disease resistance, improved nutritional quality or higher yield can be linked with a specific marker, many hundreds or even thousands of young plantlets can be screened for the likely presence of the trait without the necessity of growing all the plants to maturity or doing costly and time-consuming physiological or biochemical assays. While the earlier molecular markers like RFLPs were relatively expensive, newer markers like microsatellites and SNPs (single nucleotide polymorphisms) are considerably cheaper and easier to use. The use of molecular markers can decrease the timescale of crop breeding programmes by several years and can substantially reduce costs. Although largely limited to the major temperate crops at present, the same technology can be applied to assist the breeding of any crop and even to domesticating entirely new crops. A good example of the potential for marker-assisted selection can be seen with edible tree crops, many of which are major export earners for developing countries. Examples of such crops include oil palm, coconut coffee, tea, cocoa and the many fruit trees like bananas and mangoes. Due to the relatively long life cycles and the formidable bulk of tree crops, even as seedlings, research into their biology has always been a relatively difficult undertaking. Hence the application of modern scientific breeding methods, as used for many decades with non-tree crops, is only just beginning to be done for trees.

Tissue culture and mass-propagation

The –use of modern techniques of cell, tissue and organ culture is central to many crop improvement programmes in both industrialised and developing countries. Indeed the limiting step to the successful development of GM varieties of the major edible crops has not been transgene insertion itself, but rather the regeneration of viable plants from the transgenic explant material. Tissue culture has been widely used in crop breeding programmes for over 50 years (Phillips, 1993). For example, the use of embryo rescue techniques has enabled the incorporation of characters like disease resistance from wild relatives of crops into elite breeding lines. It is now possible to make wide crosses between hexaploid wheat and barley, rye or diploid wheat. The hybrids of such crosses are sometimes sterile due to embryo abortion but can be “rescued” by culturing or transplanting the embryos. Another important technique that is increasingly used in crop breeding programmes is the production of doubled haploids. The repeated selection of heterozygous materials in a breeding programme can increase uniformity, but many generations are required to reach homozygosity in loci associated with agronomic traits. The artificial production of haploid plants followed by chromosome doubling offers the quickest method for developing homozygous breeding lines from heterozygous parental genotypes in a single generation. Haploid gamete cells from anthers or ovaries can be converted into diploids after colchicine treatment and then regenerated to yield doubled haploid plants. This technique is now used widely for the improvement of many of our most important crops, including all of the major cereals as well as potatoes, brassicas and even some trees (Forster et al, 2000).

Yet another useful application of tissue culture methods is the mass clonal propagation of certain crops, in particular trees. The need for the rapid multiplication of millions of seedlings for edible crops like chicory or for new biomass crops like Miscanthus (Lewandowski, 1997), has led to the development of automated methods for their clonal propagation (Hayashi et al., 1992). Clonal propagation has not always been commercially successful, however. In the 1980s, a scheme to mass propagate millions of oil palm plantlets from a superior breeding line foundered when many of the maturing trees were discovered to have an abnormality in their floral development (Corley, 2000). This led to a failure of fruit formation and, since the major products of the crop are fruit oils, the trees were effectively useless. The abnormality is now known to be due to a tissue culture effect whereby the expression of a homeotic gene regulating meristem identity is disrupted. Although the problem has now largely been rectified by further research, commercial confidence in clonal propagation has not recovered and very little planting of clonal oil palm has been done over the past 20 years (Corley, 2000).

The continuing scope for crop improvement following the identification of higher yielding germplasm and its multiplication by mass-propagation can be exemplified once again by considering the case of oil palm. Oleic acid rich oil from palm mesocarp is the most important edible oil crop produced in Asia. In addition, palm kernel oil is also the most widely used oleochemical feedstock for the manufacture of detergents and other lauric-based products. Over the past decade the average yield of Malaysian palm oil on plantations has stagnated at 3.5-3.8 $T.ha^{-1}$. This is despite the availability of new clonal lines that can yield as much as 7.5 $T.ha^{-1}$ (Ginting et al., 1995). Malaysia currently produces about 13.5 $MT.yr^{-1}$

of palm oil worth an annual $4 billion: this is in a country with a total GNP (gross national product) of $60bn. To put this figure of $4 billion into context, the estimated entire revenue generated by the US agbiotech sector in 1999 was just $2.3 billion – and this included all the companies supplying inputs to the sector or its employees (Ernst & Young, 2000). Therefore, the effective *doubling* of the palm oil yield that could be implemented following a successful mass-propagation programme could contribute a significant 6.6% extra to the overall gross national product of this single Asian country. The application of a similar strategy with other tree crops, or even relatively undomesticated annual crops, could also yield equally striking results that would particularly benefit developing countries.

Genomics

Genomics is the term given to the massively parallel study of the DNA and protein sequences in an organism and also when and where such sequences are expressed (the term "proteomics" is sometimes used for studies of protein sequences, but proteins will be discussed here as part of genomics). However, genomics is much more than the mere assembly of DNA or protein sequence information or gene expression catalogues. It can also be used a tool in crop breeding programmes and even for the domestication of new plant species as future crops. Many traits of agricultural importance in crop plants appear to be regulated by a large number of genes and therefore do not segregate into simple Mendelian ratios, as would be expected if only one or two genes were involved. Examples of such complex traits include height, branching, seed oil and protein yield, oil quality and flowering time. During the past few years, however, the use of more sophisticated genomic tools has shown us that, although dozens of genes may underlie such complex traits, sometimes much of the variation in their phenotypic expression can be caused by a small number of key regulatory genes. These genes can now be identified and mapped based on sequence similarities, expression profiles and molecular markers.

Genes that play a major role in regulating agronomically relevant complex traits in model plants like *Arabidopsis*, and also some crops like maize, are now being isolated at an ever-increasing pace. Examples include height, flowering time, vernalisation, shattering of seed pods and stem branching. Many of these plant genes encode transcription factor proteins that in turn regulate the expression of large sets of other genes. For example, transcription factors can switch on entire metabolic pathways or patterns of cell division, resulting in the formation of new tissues or organs and the accumulation of new storage products (Murphy, 1998). The isolation and mapping of important regulatory genes from a model plant species like *Arabidopsis* or rice will soon enable the equivalent gene(s), in terms of both sequence and chromosomal location, to be isolated from other plants, including most of the major crop species. This is due to a striking feature of many higher plant genomes, namely their high degree of similarity to one another in terms of the structure of their genes and, in related species, the order in which they occur on chromosomes. This gene order, or synteny, is particularly well-conserved in monocotyledonous plants, which include all of the cereal crops. Recent evidence suggests that there is also appreciable genome synteny within the dicotyledons, which include the important model plant *Arabidopsis* as well as major crops like soybean, rapeseed and tomato (Grant *et al.*, 2000; Casci, 2000).

In the longer term, there are many potential applications of synteny-based genomic approaches to crop improvement. For example, they open up the prospect of being able to manipulate some of the most basic features of crop plants without involving transgenesis. Key agronomic traits identified from model plant genomic studies can often be mapped to their syntenic equivalents in a crop of interest. This information could then be used to generate molecular markers to assist breeding programmes seeking to manipulate such traits. In annual crops, the height and branching could be adjusted to optimise harvestability and the capacity of the plant to bear and retain its seed. The seeds could be selected to accumulate the exact mixture of carbohydrate, protein, oil and fibre required for a particular end use. Flowering time could be adjusted to suit particular climatic conditions. For example, the development of earlier flowering varieties of some crops in a location like the Canadian prairies would allow them to set seed and be harvested before the onset of early frosts that can otherwise halt seed development before it is completed. A slight advancement of flowering time could also dramatically improve yields of rice in some tropical and subtropical regions where the current growing season is just over six months. If the length of the growing season could be reduced to less than six months, the farmers in such regions could grow two rice crops in each year. The development of shorter varieties of cereal grain crops in the 1960s and 1970s led to such huge increases in yields that it was dubbed the 'Green Revolution'. However, some crop varieties, including the highly prized Basmati rice, have remained recalcitrant to efforts at introducing dwarf traits by conventional breeding. The ability to alter height by direct gene manipulation is therefore an attractive prospect.

Transgenic uses of agbiotech

The present commercial use of transgenic crops is almost entirely limited to the manipulation of a few input traits in a very small number of major commodity crops, although such crops now comprise a considerable and still-increasing proportion of the total acreage in the USA (see below). However, there are also many other examples of potential transgenic crops being developed with modified output traits. The US Biotechnology Industry Organisation provides a list of transgenic and non-transgenic agbiotech products that are either already on the market or under development for release in the next six years (Biotechnology Industry Organisation Server. http://www.bio.org/er/agriculture.asp).

In 2001, worldwide plantings of transgenic crops exceeded 52 Mha, although such crops were overwhelmingly concentrated in the Americas, with the USA, Argentina and Canada accounting respectively for 68%, 22% and 6% of the total (International Service for the Acquisition of Agri-biotech Applications www.isaaa.org). To put this figure into context, 52 Mha is equivalent to more than twice the total land area of the United Kingdom. The major transgenic crop species were soybean with 68% total area, maize with 22%, cotton with 13% and rapeseed with 5%. There were also much smaller commercial plantings of transgenic potato, squash and papaya. It is estimated that this area of transgenic crops could triple in the next five years (Abelson & Hines, 1999). The development of only a few commercial transgenic crop species to date reflects the relative technical difficulties in gene transfer in some of the other major crops like wheat and barley plus a focus on the development of temperate crops by commercial companies rather than less profitable subtropical staples like rice.

The genetic transformation of virtually all of the major annual crop plants has now been achieved, although in many cases this remains a time-consuming and costly technical achievement. For example, the transformation of soybean by gene transfer into cultured embryos is a relatively lengthy, inefficient and labour-intensive process. Even in some of the species like rapeseed, where transformation is relatively facile, it is often highly cultivar-dependent. This means that it may not be feasible to transform the current elite rapeseed cultivars with a gene or genes of interest but instead an older variety such as Westar, which has been optimised for transformability, must be used. In order to produce a commercial transgenic variety the Westar transformant must then be backcrossed to an elite line—a process that can take several years and add significantly to development costs.

In the past few years, the use of new strains of *Agrobacterium* plus developments in tissue culture have resulted in the successful transformation of the major cereals such as wheat and rice by this method, which is generally more reliable than the previous method of choice (biolistics). This promises to facilitate the future development of transgenic cereal crops. By the year 2002, more than 30 tree species had been transformed with various genes, most of which were marker (40%) or herbicide-tolerance (24%) genes. Although there have been over 120 field trials of transgenic trees, none of these has yet resulted in commercial planting.

Input traits

Input traits are those characteristics of a crop that affect its cultivation and yield, but do not affect the quality of the products from the crop. They are typically related to agronomic inputs such as herbicides, pesticides and fungicides, as well as nitrate and mineral fertilisers. Input traits were the first commercial target of transgenic manipulation in crops for several reasons. First, the traits can often be modified by the insertion of a single gene and many of the relevant genes had already been isolated by the mid-1980s. Second, seeds harbouring the new traits would have an added value that could be readily captured by the company that developed them, hence rapidly offsetting the R&D costs. Third, the end result should be better yields and/or lower production costs; no changes in harvesting methods are needed and no new crop products have to be processed. This made the development of transgenic crops with enhanced yield traits an attractive short-term proposition for the seed companies who developed this first generation of GM crops. In the 2001-2002 season, virtually all of the commercially cultivated GM crops were modified for input traits. The main commercial downside of this strategy has been that consumers have no perceived benefit from such crops, which produce the same foods at the same price as conventional crops. On the other hand, many consumers (especially outside the Americas) have perceived a risk from GM-derived foodstuffs.

Herbicide tolerance

The most widespread types of transgenic herbicide-tolerant crops are those developed by Monsanto under the trade name of "Roundup Ready" (www.monsanto.com). Such crops are resistant to the widely used broad-spectrum herbicide, glyphosate, which is marketed by Monsanto as 'Roundup'. Glyphosate is a toxin that inhibits the enzyme 5-enolpyruvyl shikimate 3-phosphate synthetase (EPSPS) in plants, resulting in a lethal disruption in their ability to synthesise proteins. Although all known plant versions of EPSPS are highly sensitive to inhibition by glyphosate, many bacteria have a slightly different form of the enzyme that is insensitive to the herbicide. Therefore, if a copy of a bacterial EPSPS gene is inserted into a crop plant, the resulting transgenic crop variety will be resistant to applications of glyphosate while all non-transgenic plants in the same area will be killed. The cultivation of transgenic glyphosate-resistant crops is claimed to result in significant financial benefits for farmers because of reduced overall herbicide applications and higher yields per hectare (reportedly worth \$15–28 ha^{-1}). For their part, the seed companies are able to sell a profitable package, including seeds and herbicide, to the growers.

A similar package of herbicide-resistant transgenic crops, plus the related herbicide, has been developed by Agrevo under the trade name of 'Liberty Link' (http://www.archive.hoechst.com/english_3er/publikationen/future/ernaehr/art7.html). In this case, the herbicide is the fungal toxin, glufosinate, which is marketed under several names including 'Basta' and 'Challenge'. This widely used compound is an inhibitor of glutamine synthase in plants, causing a disruption of photosynthesis that results in the death of the entire plant within a few days. Glufosinate is a broad-spectrum (*i.e.*, non-specific) herbicide and its use is therefore limited to total eradication of vegetation or to control weeds shortly after crop emergence. In contrast, glufosinate-resistant crops can be sprayed with the herbicide at any time, resulting in the effective elimination of all other plants from the field. Resistance to glufosinate is conferred by the addition of a gene from the soil-dwelling bacterium *Streptomyces viridochromogenes*, which encodes the enzyme phosphinothricin acetyltransferase. This enzyme is able to acetylate glufosinate, which results in the loss of its toxic activity. Transgenic plants expressing this transgene are therefore able to grow normally, even after the application of relatively large doses of the glufosinate. Transgenic glufosinate-resistant rapeseed was first grown commercially in Canada in 1995, soybean and maize were approved in 1997, and other crops such as sugar beet will soon be available.

There are concerns that in some crops like rapeseed or sugar beet, which have closely-related weed species, the herbicide-resistance trait may spread into the weed population by cross-pollination. However, non-transgenic herbicide-tolerance has also been developed in rapeseed and other crops. For example, the so-called SMART-canola varieties of Canadian rapeseed developed by American Cyanamid (now owned by BASF), are resistant to imidazolinone herbicides but are the products of conventional (*i.e.*, non-transgenic) plant breeding. These crops have been grown since 1995 and their use is widespread in Canada (www.bio.org/food&ag/approvedag98.html). In principle, such non-transgenic herbicide-resistant crop varieties are as likely to outcross and transfer their resistance traits to weedy relatives as the transgenic varieties. Therefore, concerns about the spread of traits like herbicide-tolerance should not only be related to the use of transgenic crops *per se*, but rather involve more general issues of the management of any agronomic trait where its transfer to weedy relatives, or elsewhere, may have deleterious consequences.

Pest and disease resistance

Crop yields are regularly reduced by herbivore attack, most notably from insects, and by diseases caused by nematodes, fungi, bacteria or viruses. Even in intensively managed agronomic systems, losses of >30% from various pests and diseases are commonplace; while in developing countries the figures are much higher. After herbicide tolerance, the second most common modification in transgenic plants in 2001 was insect resistance, which alone accounted for 8 Mha, plus a further 4 Mha where the trait was expressed in combination with herbicide tolerance (www.isaaa.org). Insect resistance in transgenic maize, cotton and potatoes was conferred by insertion of a gene encoding a protein toxin from the gram-positive soil bacterium *Bacillus thuringensis* (Bt). The use of insect-control sprays containing a live toxin-producing *Bacillus thuringensis* suspension has been common for over 30 years in organic farming but the widespread use of Bt toxins in transgenic crops is much more recent. The Bt toxins are a family of so-called crystalline (cry) proteins that are converted into their active form during digestion in the gut of a range of insect larvae, resulting in a disruption of potassium ion transport that rapidly becomes lethal (www.nal.usda.gov/bic/BTTOX/bttoxin.htm). Mammals do not convert the toxins into their active forms and are therefore unaffected by them. Early indications (Briggs and Koziel, 1998) suggest that transgenic Bt crops are effective in controlling insects and improving yields (by 7%), while also reducing the need for spraying with more toxic and less desirable pesticides that often affect beneficial organisms such as insectivorous birds (saving growers some \$40 ha^{-1}).

The obvious danger in relying on a single class of toxins is that it tends to establish a strong selection pressure favouring the survival of insects that are able to sequester the toxin or otherwise render it harmless. Before the mid-1990s, only a few thousand hectares of land on organic farms were sprayed annually with live Bt, but in the last few years the cultivation of transgenic Bt crops has expanded to over 11 Mha and this area is still increasing. The resultant chronic and widespread exposure of hundreds of insect species to the Bt toxin must increase the likelihood that resistance will eventually develop in some species.

Viruses, bacteria, fungi and nematodes are major pathogens of crops and there has been much research aimed at producing resistant varieties by transgenic approaches. While various fungicides and nematicides are available to help farmers control these pathogens, there are no equivalent virus-control agents, so the combating of viral diseases normally relies on the endogenous resistance of the plant. In the absence of endogenous resistance, viral infections can be particularly devastating to a crop. This has stimulated efforts to engineer viral resistance into transgenic crops. The commercial cultivation of several transgenic potato, squash and papaya varieties with virus-resistance genes has already been approved in some countries (http://www.isaaa.org/publications/briefs/Brief_8.htm), and advanced field trials are underway in others. These transgenic crops express complete or partial proteins from a particular virus (typically part of the viral coat protein complex), which causes the plants to become sensitised to subsequent infections with the same virus. When such plants are attacked by the viral pathogen, they mount a successful defence response in a manner that is somewhat analogous to immunisation in animals that have been injected with an attenuated virus, although the exact mechanism of viral immunity in plants remains to be explained. A recent example of a transgenic virus-resistant crop is a papaya variety developed in Hawaii and in Australia. The papaya ringspot virus is a major threat to the cultivation of papayas in tropical countries like Hawaii. Transgenic papayas that express the ringspot virus coat protein, which on its own is harmless to the plants, are considerably more resistant to infection with the active virus than are non-transgenic papayas. Meanwhile, efforts to obtain improved virus-resistant strains of wheat continue, using both transgenic and non-transgenic approaches (Sharp et al, 2002)

In summary, the first generation of transgenic crops has been almost entirely engineered for two classes of input traits, namely herbicide tolerance and disease resistance. Since these manipulations are not designed to improve food quality, there have been little or no perceived advantages of the resulting GM crops to consumers. Indeed, in some cases the presence of additional proteins encoded by the transgenes has raised fears of a reduction in edible quality of the crop products. An example was the STARLink maize developed by Aventis and widely grown in the USA until 2000. This GM variety of maize expressed the insecticidal protein *cry9c*. Since *cry9c* is not present in normal human diets, the Environmental Protection Agency (EPA) in the USA only authorised use of STARLink maize in animal feed formulations until it could be demonstrated that the protein did not cause allergies in humans. However, it was subsequently found that taco shells on sale in US supermarkets contained the *cry9c* protein, which meant that there had been a failure to segregate and monitor the GM maize, either on the farm and/or during its subsequent processing to flour (Kaiser, 2000). Ironically, it now appears that cry9c is not particularly allergenic, but meanwhile the damage had been done and consumer confidence in the ability of the agbiotech industry to segregate different GM and non-GM crops has been dented. This situation was not helped when in August 2002 a Scottish research institute discovered that Aventis had been growing an unapproved GM variety of rapeseed in field trials in the UK for at least two years (http://www.defra.gov.uk/news/2002/020815a.htm). In the future, it will be important for the industry to tighten up its monitoring methods, especially as newer classes of both GM and non-GM crops with modified quality traits are cultivated and consumed on a commercial scale that could involve anything from a few tens of hectares to millions of hectares for each new variety.

Future applications of agbiotech

As we progress beyond the first generation of mostly input trait related transgenic crops, it may be useful to take stock of the potential for the development of new types of improved crops over the next decade or so. As described above, emerging developments in the application of genomics to agbiotech may allow for some radical modifications of plant architecture, growth habit and composition. Not all of these crops will be transgenic. Evidence is already emerging that it may be possible to use non-transgenic methods to alter some fundamental aspects of plant growth and development, including salt tolerance in certain cereals (Forster et al, 2000), quality traits like fatty acid quality in oil crops and even input traits like herbicide tolerance (http://www.clearfieldsystem.com/html/gmo.html). Nevertheless, such manipulations will always be limited by the composition of the genome of the crop(s) concerned. In order to introduce completely novel traits into crops there are two possible approaches. Firstly there is the "conventional" transgenic strategy whereby a gene(s) of interest is added to an existing crop in the hope that it will express a new and useful trait. Examples include engineering oil crops to accumulate nutritionally desirable ω-3 fatty acids like eicosapentenoic (EPA) or docosahexenoic (DHA) acids or industrially useful short-chain fatty acids like decanoic acid. Secondly, there is the less conventional but increasingly realistic prospect (thanks to genomics) of domesticating plants that already make useful fatty acids so that they can be developed as commercially viable crops. Both strategies will be discussed below.

Edible oil-based products

Annual and perennial crops produce a yearly output of >87 Mt in traded vegetable oils that is worth about $40–45 billion. Plant-derived oils are mainly used as commodities for the manufacture of foodstuffs. Oil crops are second only to cereals as a source of calories for human societies as well as providing essential fatty acids like linoleic acid plus many of the lipid-soluble vitamins, including carotenoids (vitamin A) and tocopherols (vitamin E). Some plant oil-derived foodstuffs, such as cooking oils, margarine or chocolate are quite obviously lipidic and are referred to as visible fats. However, the vast majority of the plant oils that are consumed in the western diet are the so-called "invisible" fats that lurk in over half of all the food products in a typical supermarket. These invisible fats are found in nearly all processed foods including biscuits, shortenings, cakes, breads, many canned foods, frozen foods, yoghurts, milk substitutes, spreads and dips, to name but a few.

Although there are many possible modifications that could improve the edible quality of plant oils, two particular targets are particularly sought after at the present time. The first target is to reduce or eliminate C18 polyunsaturated fatty acids, such as linoleic and α-linolenic from some seed oils. This would avoid the need for chemical hydrogenation that is necessary to improve oxidative stability of many plant oils, as well as to convert some liquid oils into solid fats like margarines. Chemical hydrogenation results in the production of *trans*-fatty acids, which many people believe to be undesirable in the diet. Although the evidence that *trans*-fatty acids can be harmful is by no means undisputed (http://www.healthcastle.com/trans.shtml), there is sufficient public awareness of these health claims that many food manufacturers have already started to promote products that have reduced or zero levels of *trans*-fatty acids. The extent of *trans*-fatty acids in foods may well become even more apparent if the US Food and Drug Administration (FDA) proceeds with current plans for their mandatory labelling in all food products. The proposed rule changes would allow for a new nutrient content claim, "*Trans Fat Free"*. The FDA is expected to issue a final rule on this matter early in 2003. Already, Dupont has produced a GM soybean variety where genes encoding the C18 oleate and linoleate desaturases have been down-regulated, leading to the production of an oil that contains over 80% oleic acid and only trace levels of polyunsaturates (http://www.usembassy.org.uk/fas/pdf_reports/kerr.pdf).

The second target for dietary oil improvement is to increase the amount of the very long chain (C20–C24) ω-3 polyunsaturates, such as DHA or EPA. These fatty acids are nutritionally beneficial precursors of hormones and physiological effectors such as prostaglandins, leukotrienes and thromboxanes. Higher plants do not normally accumulate >C20 ω-3 polyunsaturates, although there is a report of a single gymnosperm, that has low levels of EPA and arachidonate in its seed oil (Wolff et al, 1999). On the other hand, fish and other marine creatures accumulate oils that are rich in DHA and EPA but in recent years stocks have been drastically depleted by overexploitation, leading to the virtual elimination of some fisheries like the North Atlantic cod. It is estimated by the FAO that the shortfall between the annual demand for seafood and its supply from wild fisheries will be 50 Mt by 2025: it is most unlikely that fish farms can compensate for this shortfall. The resulting decrease in availability and high prices for marine oils make it necessary to consider alternative sources of these useful fish-derived fatty acids, particularly for less affluent groups in the population. In the past few years there has been considerable progress in identifying and isolating many of the genes that are responsible for the synthesis of DHA and EPA. It is, therefore, possible that transgenic varieties of crops like rapeseed that make DHA and EPA will be produced before the end of the decade. Several research groups are already attempting to engineer GM varieties of oil crops with elevated levels of ω-3 polyunsaturates by transferring genes from other organisms (Beaudoin et al, 2000). An alternative, non-transgenic approach that is becoming increasingly popular is to culture some of the many species of microalgae that can synthesise these fatty acids (Jeffrey, 2001). Numerous companies and public research institutes are currently attempting to develop biotechnological methods for the large-scale commercial production of algal lipids for the food industry.

Another category of plant lipid of interest to the food industry is the phytosterols. Margarines enriched in phytosterols extracted from (non-transgenic) wood pulp or vegetable oils have recently been marketed and, despite an appreciable price premium compared to conventional margarines, they have enjoyed modest commercial success. The appeal of the phytosterol-enriched margarines is based on evidence that they may help to reduce blood cholesterol levels and hence combat heart disease. Such products could be made more cheaply if more of the phytosterols were synthesised in the same seeds as the oil from which the margarine is derived and efforts are underway to up-regulate phytosterol biosynthetic pathways in transgenic plants. It has been surmised that the widespread availability and consumption of low cost, phytosterol-enriched margarines could eventually have an impact on national rates of cardiovascular disease – still the number one killer of people, especially in low-income groups, in all industrial societies (Howard & Kritchevsky, 1997; Plat & Mensink, 2001).

Probably the best-known recent example of a nutritionally enhanced crop is the development of the transgenic 'golden rice' by a Swiss-based group (Ye *et al.*, 2000). The grains of this GM rice variety are yellow because they have been engineered to accumulate the lipophilic pigment, *β*-carotene (provitamin A), which is normally absent from rice grains. The transgenic rice contains three inserted genes encoding the enzymes responsible for conversion of geranyl geranyl diphosphate to β-carotene. It is claimed that consumption of this rice by at-risk populations may alleviate the vitamin A deficiency (leading to night blindness) that currently afflicts some 124 million children worldwide. Such claims are hotly disputed by anti-GM groups (e.g. Greenpeace Server. http://www.greenpeace.org/~geneng/) and the "golden rice" has yet to prove itself in large-scale field and nutritional trials in the target developing countries. Interestingly, the rights for the commercial exploitation of "golden rice" in developed countries, including the USA and Europe, have now been acquired by Syngenta. It is possible that this could lead to the marketing of "vitamin-enhanced" food products derived from golden rice, e.g. in breakfast cereals, which may be more acceptable to the public than the current generation of food from input trait modified GM crops.

Oleochemicals

About 20% of the total output of plant oils is used as a feedstock for the production of oleochemicals. Over the past century, plant oil crops were nearly all bred to provide edible products and their fatty acid compositions are therefore quite restricted, being mostly limited to C16 and C18 saturates and unsaturates. There are many desirable changes that could be made to enhance the industrial uses of plant oils and the use of transgenes to effect such modifications has been an attractive option. Indeed, the current list of transgenic crops approved for general release in the USA includes only two crops with modified seed quality traits, both with altered oil profiles. By changing the chain length and functionality of the fatty acids it is possible, in principle, to produce oils with carbon chain lengths from C8 to C24, containing anything from 0 to 5 double bonds or other useful chemical functionalities such as hydroxy, epoxy or acetylinic groups. Such oils can be used for the manufacture of products such as adhesives, paints, detergents, lubricants, nylons, cosmetics and pharmaceuticals, to name but a few. Many oil-bearing seeds already produce some of these novel and potentially useful fatty acids, and such plants have been used as sources of genes for transfer into mainstream oil crops in the hope that the latter would accumulate the novel oils.

The future of GM oil crops

Despite the initial optimism of many researchers (including the author), the use of agbiotech to manipulate the fatty acyl composition of oils has turned out to be more complex than was first thought. Indeed, very recent findings suggest that our understanding of even the basic pathway of triacylglycerol oil biosynthesis is far from complete and that there are probably multiple pathways rather than just one (Murphy, 2003). The consequence of these complexities of plant lipid metabolism has been that, although there have been many impressive achievements in isolating oil-related genes and producing transgenic plants with modified oil compositions, it has not been yet possible to achieve the kind of high levels, *i.e.* 80–90% of novel fatty acids that will make possible their widespread commercial exploitation (Murphy, 1999).

The only commercially grown transgenic crop with modified seed oil is the laurical variety of canola (rapeseed) originally marketed by Calgene in 1995. From an original level of 40% lauric acid newer laurical varieties have been produced with 40% to 60% lauric by the insertion of several additional transgenes (Voelker et al 1996). However, this crop remains far from being a commercial success and cannot compete with cheaper tropical lauric oils from coconut and oil palm.

The availability of many genes involved in fatty acid modification and the good progress in transforming the main oil crop species will doubtless encourage further efforts to resolve the challenge of low levels of novel fatty acid production. But even if such efforts are successful the commercial success of transgenic oil crops will remain problematic. It will be necessary to identify or develop robust markets for their products—simply substituting for petroleum-derived products is unlikely to be economic for several decades at least, if at all (Murphy 2003). The additional costs of identity preservation may preclude the use of such transgenic oils as large-scale commodities in competition with conventional plant oils, even for industrial applications. One exception may be if governments intervene in markets to actively promote transgenic plant oils. Recently the European Commission proposed a directive (COM (2001) 547) which would allow the member states to give up to a 50% tax reduction on biofuels in relation to the corresponding fossil fuels (http://europa.eu.int/comm/taxation_customs/proposals/taxation/tax_prop.htm). This directive does not itself apply to transgenic oils but is an example of how governments might manipulate markets to promote their use in the future. It is also possible that some plant-derived oils will substitute for niche applications where the cheaper mineral oil based products may have environmental drawbacks as may be the case with some lubricants, where soy oils might be a commercially valid replacement (Canadian Agricultural New Uses Council, 2000: http://www.canuc.ca/New%20Use%20Documents.nsf/61b9b855111b4a7188256a05000a1f52/f226200fcaa976e088256a05000b4109/$FILE/ts4.pdf). In summary, transgenic oil crops may have considerable promise for the long-term future but their commercial prospects over the next few years remain uncertain.

Bioplastics

Virtually all of our conventional plastics are made from non-renewable petroleum-derived products such as adipic acid and vinyl chloride. An alternative is to harness the ability of soil bacteria like *Ralstonia eutrophus* that are able to accumulate up to 80% of their mass in the form of non-toxic biodegradable polymers called polyhydroxyalkanoates (PHAs). The PHAs are made up of *β*-hydroxyalkanoate subunits that are synthesised from acetyl-CoA via a relatively short pathway involving as few as three enzymes for the most common PHA, polyhydroxybutyrate. During the 1980s and 1990s, the UK-based company, ICI, developed a fermentation process to produce PHB and other PHAs in transgenic *E. coli* cultures expressing PHA genes obtained from bacteria such as *Ralstonia eutrophus*. However, the price of the resulting plastic was ten-fold higher than that of conventional plastics. Despite the enormous environmental benefits of these biodegradable plastics (they can be composted into soil and degrade completely in a few months), their high cost has rendered them uneconomic for large-scale production. Interestingly, there is a small but lucrative niche market for biodegradable plastics as the framework of artificial tissues. Following their insertion into the body, the PHAs are gradually broken down and the body reassembles the natural tissue in the same shape as the original PHA template. In such a specialised medical application, the price of this kind of PHA product is obviously not as important as for lower-value materials like plastic toys, pens or bags, *i.e.* high-value applications tend to relatively be price-elastic whereas commodities are not.

The cost of PHAs could be considerably reduced if they were produced on an agricultural scale in transgenic crops. This prospect led Monsanto to acquire rights to PHA production from ICI/Zeneca in the mid 1990s and to transfer the bacterial genes into transgenic rapeseed plants. Providing the PHAs accumulate in the plastids, and not in the cytosol, it is possible to obtain modest yields of the polymer from either leaves or seeds. A major and as yet unresolved technical hurdle is how to extract the polymer from the plant tissue in an efficient and cost-effective manner. Another complexity is that polyhydroxybutyrate, which is the most widespread PHA, is a rather brittle plastic and is not suitable for most applications. The best plastics are co-polymers of polyhydroxybutyrate with other PHAs like polyhydroxyvalerate, and the production of such co-polymers in transgenic plants is considerably more difficult than that of single-subunit polymers. In May 2001, these perceived difficulties coupled with its own cash-flow problems prompted Monsanto to sell its transgenic PHA business to Metabolix. (Metabolix Server. http://www.metabolix.com/natures%20plastic/coretechnology.html). Metabolix is now involved in a joint venture with the US Department of Energy worth $14.8 million with the aim of producing PHAs in transgenic plants over the next 5 years. There are several other groups attempting to make PHAs in plants (including one in oil palm) and it will be interesting to see whether these environmentally friendly products can indeed be produced as a viable commercially venture.

A second category of bioplastics is the polylactides (PLAs), which are based on lactic acid. The PLAs are not the result of transgenic crop production (unlike PHAs) but are products of a non-transgenic application of agbiotech. The lactic acid feedstock for PHA synthesis can be obtained by fermenting starch from any crop with a sufficiently high starch content. A joint venture company called Cargill Dow Polymers (www.cdpoly.com) has recently developed a low-cost method of heating up lactic acid monomers to form PLAs with the appropriate mixture of D- and L-isomers to confer the optimal physical properties to form stable and durable polymers. These polymers form a glossy transparent thermoplastic with properties similar to polycarbonates and polyesters that can also be used to make acrylic-like fibres for clothing. The so-called "Nature Works^{TM}" PLA products will be fully biodegradable and compostable. In late 2001, the first full-scale production facility for Nature Works^{TM} PLA opened in Blair, Nebraska, with plans to build a second unit in Europe at a later date. The Nebraska factory uses maize as the feedstock (sugar beet can also be used) and it is planned to produce 140,000 t yr^{-1} of PLA. This is an interesting alternative way of making biodegradable plastics that could be used in medium-value markets like textiles and do not come from transgenic plants. One of the first applications of Nature Works^{TM} fibres is for the manufacture of performance fabrics aimed at the outdoors and sportswear markets (http://www.costumegallery.com/Textiles/corn.htm). Despite the reservations from some quarters, PLAs and related bioplastics certainly merit further investigation.

Developing new non-GM crops

Most of our global agricultural production relies on a very limited number of widely cultivated staple crops, such as wheat, rice, maize and soybean. The introduction of transgenic varieties of these major crops is likely to increase their dominance further. This may be particularly true if output traits are modified so that the crops accumulate new products and so require even larger acreage. In some cases, the transgenic crop may produce a compound currently obtained from a minor crop, resulting in displacement of the latter. These trends may be undesirable for ecological reasons as they increase the tendency towards extensive monocultures that may be more susceptible to pests or diseases. However, a more compelling argument against a proliferation of transgenic mainstream crops with novel output traits is the problem of segregation. A feasible alternative strategy is to develop new crops as sources of the novel products. As well as being more easily segregated, the new crop species will already synthesise the products of interest without the need for convoluted manipulations of biochemical pathways and the possible side effects that may ensue. Oil crops provide a useful example of the way such new crops might be developed.

Almost 86% of world production of traded plant oils is derived from only four major oil crops: soybean, oil palm, rapeseed and sunflower (Gunstone, 2000). Each of these crops currently produces mainly edible-grade oils and they are not optimised for the production of novel and unusual fatty acids. The use of transgenic methods to increase the diversity of fatty acid content in these major crops has made great strides in the past fifteen years but significant challenges remain. However, there is also an enormous diversity of naturally occurring plant species, many of which already produce a wide range of industrially useful fatty acids. Some of these plants can already accumulate over 90% of a single exotic fatty acid in their seed oil (Murphy, 1996). Therefore nature provides us with a ready made source of almost any type of fatty acid from C8 to C24, and containing a huge variety of functionalities (a comprehensive list of novel oilseeds is available on the USDA new crops database on http://www.ncaur.usda.gov/nc). Such plants also have an advantage over some of the newer transgenic crops in that they are already adapted to accumulate these exotic fatty acids only in their storage oil—these fatty acids are hardly ever found in cell membranes or any other lipids where their presence could be damaging. A further advantage of these novel oilseed crops is that the seed oils already contain accessory stabilising agents, such as antioxidants, which prevent the breakdown of some of the more highly reactive fatty acids such as conjugated polyunsaturates and those containing acetylenic bonds. Many issues relating to new crops are discussed in the book edited by Janick (1999) or on the Purdue University new crops website (www.hort.purdue.edu/newcrop).

Challenges and possibilities for new crops

Although many of the potential new crops may already be excellent sources of useful products, such as novel fatty acids, they are often not yet suitable for large-scale agriculture. The reason for this is simple: these plants have not been optimised for agronomic performance over centuries or even millennia, as have some of our more familiar crops. They suffer from the usual characteristics of wild plants; for example, they tend to flower asynchronously throughout the summer and therefore do not produce their seed at a single time, which makes harvesting very difficult. They often produce seed pods that are prone to shatter before or during harvest, resulting in a loss of many of the seeds. Often, the canopy architecture of the plant is not suitable for existing harvesting machinery. They may be susceptible to a variety of diseases or pests, including fungi and insects. Finally, in the case of oilseeds, although they may have contained as much as 90% of a novel fatty acid in their seed oil, the overall oil yield in tonnes per hectare may be relatively low. Of course, all the reservations about the economic viability that are mentioned above for transgenic oil crops will also apply to new oil crops.

The improvement of these important agronomic characters requires the manipulation of numerous complex traits. Companies are often dismayed by the prospect of domesticating new species, citing the example of major crops such as wheat, which is still being improved after more than 10,000 years of domestication. Nevertheless, we can now be more optimistic about the prospects for crop domestication. Many of our newer edible oil crops have been improved by scientific breeding techniques over the past 50 years much more rapidly than wheat. Examples of such crops include hybrid maize, rapeseed, sunflower and soybean, which have only been grown as mainstream crops for a century or less. There is also now the prospect of using biotech methods to accelerate the development of new crops.

Conclusions

Plant biotechnology has made great strides over the past decade and has now emerged from its genesis in research labs into the mainstream of commercial agriculture, with well over 50 Mha of transgenic crops grown in 2002. The new genomic and post-genomic technologies have great promise for both conventional crop breeding and the engineering of new transgenic varieties. Hundreds of new genes have been cloned that have potential applications for traits as diverse as vaccine production and salt tolerance.

Nevertheless, it is not a uniformly rosy picture for agbiotech in the early years of the 21st century. The range of traits being modified and the number of participating countries are both very limited for a technology that was first commercialised a decade ago. Transgenic crops are still effectively excluded from large areas of the world, including some of the major industrialised trading blocs. There is a vigorous coalition of groups opposed to genetically engineered crops that is increasingly active, even in the "transgenic heartland" of North America. The present series of input trait-modified crops confer no quality or price advantages to the average consumer and therefore have little direct appeal. In contrast, the very first transgenic foods (the Calgene FLAVR SAVR™ tomato and the Zeneca tomato paste) both of which were clearly labelled as GM products, had a direct quality/price appeal to shoppers and initially sold well. Nevertheless, both of these GM products ultimately failed in the marketplace, although for ver different reasons. FLAVR SAVR™ tomatoes were produced using inferior breeding lines and the business plan for their commercial development was seriously flawed – they were not grown after 1997 (Martineau, 2001). In contrast, by early 1999, the Zeneca tomato paste had captured almost half of the total market in those supermarkets in the UK where it was offered for sale. However, only a few months later it was withdrawn from sale in anticipation of a consumer backlash following the GM-crop "meltdown" in the UK that occurred after the Pusztai affair and subsequent adverse Press reports about agbiotech.

If consumer acceptance of GM crops is to be regained in Europe, the agbiotech industry will have to come up with products that are so appealing that they can overcome the current reluctance and distrust the sceptical European public. It is still not obvious if there will be the "killer app" (to borrow a term from computer technology) of agbiotech, but such a breakthrough is sorely needed by the industry. Whether it is edible vaccines, biodegradable plastics, vitamin-enhanced staple foods or stress-tolerant crops that emerges as a "killer-app", or something quite new, remains to be seen. In the meantime, much work is necessary to update many of the basic technologies of transgene insertion and selection in plants in order to create more predictable and more stable position-specific, single-insertion events with the removal of all unnecessary DNA from the final plant. A more constructive engagement of companies with consumer groups would also be desirable, but independent scientists can also play an important role here. For example, a better-informed and educated public is more likely to understand the often-complex issues that surround plant biotechnology. Scientists also need to reach out more to explain both the benefits and the possible risks of all forms of crop manipulation, including but not necessarily confined to transgenesis.

As an alternative to GM crops, agbiotech has also opened up many new avenues to crop improvement that do not involve gene transfer. These range from the use of tissue culture and mass propagation (especially of tree crops) to the employment of molecular markers and genomic tools for advanced selection and breeding of favourable traits. Such tools can also be used to effect the rapid domestication (i.e. in decades rather than centuries) of entirely new crops as renewable sources of industrial products or for food use. Progress on research in these areas has been encouraging over the past decade but in many cases there is still a considerable gap between the promising lab work and its commercial development. More resources should be made available for the domestication of new crops, both to provide better foods and non-edible products and to enhance the diversity of our agricultural systems, which currently rely on less than a dozen major crops for over 80% of their total output. Despite all of it challenges and the turbulent events that often surround it, plant biotechnology remains one of the most vibrant and exciting areas of biology with immense promise to contribute to human welfare over the coming years.

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